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THE REFRIGERATORS NEEDED TO KEEP THEM COLD*

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ABSTRACT

The cost of superconducting magnets and the refrigerators needed to keep them cold can be estimated if one knows the magnet stored energy and the amount of refrigeration needed. This report updates the cost data collected over 20 years ago by Strobridge and others. Early cost data has been inflated into 1991 dollars and data on newer superconducting magnets has been added to the old data. The cost of superconducting magnets has been correlated with stored energy and field-magnetic volume product. The cost of the helium refrigerator cold box and the compressors needed to keep the magnet cold can be correlated with the refrigeration generated at 4.5K. The annual cost of 4.5K refrigeration can be correlated with 4.5K refrigeration and electrical energy cost.

INTRODUCTION

It is often difficult to get a budgetary estimate of the cost of a superconducting magnet system and the helium refrigeration system needed to keep it cold. This report presents one method for making a budgetary cost estimate of both components based on knowing what these components have cost in the past. One of the difficulties with this kind of estimate is the choice of the appropriate scaling parameter.

As an example for superconducting magnets, the appropriate scaling parameters may be stored energy, average induction multiplied by the field volume, or magnet and cryostat mass. The choice of scaling parameter depends on the type of magnet being estimated.

For helium refrigeration systems, the choice of scaling parameter is easier to determine. This report uses the refrigeration capacity at 4.5K. Refrigeration at other temperatures is scaled appropriately. Liquefaction is converted to 4.5K refrigeration by the use of the refrigeration liquefaction coefficient for the machine.

THE COST OF SUPERCONDUCTING MAGNETS

As superconducting magnet systems increase in size and complexity, it is appropriate to analyze the corresponding trends in the costs of the major constituent components: the magnets themselves and the refrigeration required to maintain them in operation. Every decade or so, such an analysis appears in print, usually directed at specific applications. In the early seventies, when advances in plasma physics made prototype fusion reactors feasible, a number of interesting economic assessments of such devices were published.^{1,2} Ten years later, superconducting energy storage reached respectability and so its economics were scrutinized.^{3,4} The purpose of this paper is to take a representative cross-section of superconducting magnet systems of all types and using known costs, to put the constants of the well-known cost equations for superconducting magnets onto the 1991 basis.

The composition of our sample includes six accelerator magnets, nine dipole like MHD magnets, thirty solenoid type magnets and fourteen toroidal magnets. In size, the magnets varied from a small dipole magnet, with a stored magnetic energy of about 27 kJ to systems with stored energies in excess of 1000 MJ. Only completed systems were considered: studies, planned projects and the like were excluded from the survey.

Methodology

The system characteristics were obtained from a systematic perusal of the published literature, which included technical reports circulated among interested institutions, and confirmed by direct inquiry. For the costs, the "Technical Proposal" or its equivalent was the usual starting point, followed by an actual tracking of the project costs through information obtained from the funding agency or its representative organ. In the US, this is often simply a matter of identifying the appropriate government publication; abroad, it requires a network of helpful correspondents and friendly reciprocity. In spite of the disparity of the sources, the raw data were usually reliable to about 15%.

A magnet system was assumed to be completed on the date of its first successful acceptance test. The purpose of this artificial cut-off is to better isolate the construction costs from subsequent tuning improvements which tend to have a life and hence associated costs of their own. The actual project cost was then converted to 1991 dollars using the composite escalation index for large construction projects. Foreign project costs were converted to US currency using the exchange rate at the time of construction and then treated in the same manner as domestic projects.

Two parameters were used to characterize each system: the energy stored in the magnetic field, in MJ, without corrections for field containment, and the field-magnetic volume product, in Tm^3 . This latter parameter is in certain instances a better measure of the system performance than the energy, because it attempts to define the actual portion of the magnetic field exploited by the process or device.

Results

Figures 1 and 2 are the scatter diagrams of the cost-magnet parameter relationships for the entire sample, regardless of magnet type. The lines in each figure are least square fits to the data points. The overall cost of the magnets given in Fig. 1 can be represented by the following equation:

$$C(\text{M\$}) = 0.844 [E(\text{MJ})]^{0.459} \quad (1)$$

and

$$C(\text{M\$}) = 0.770 [\Omega(\text{Tm}^3)]^{0.631} \quad (2)$$

where C is the magnet cost; E is the stored energy, and Ω is the field-magnetic volume product.

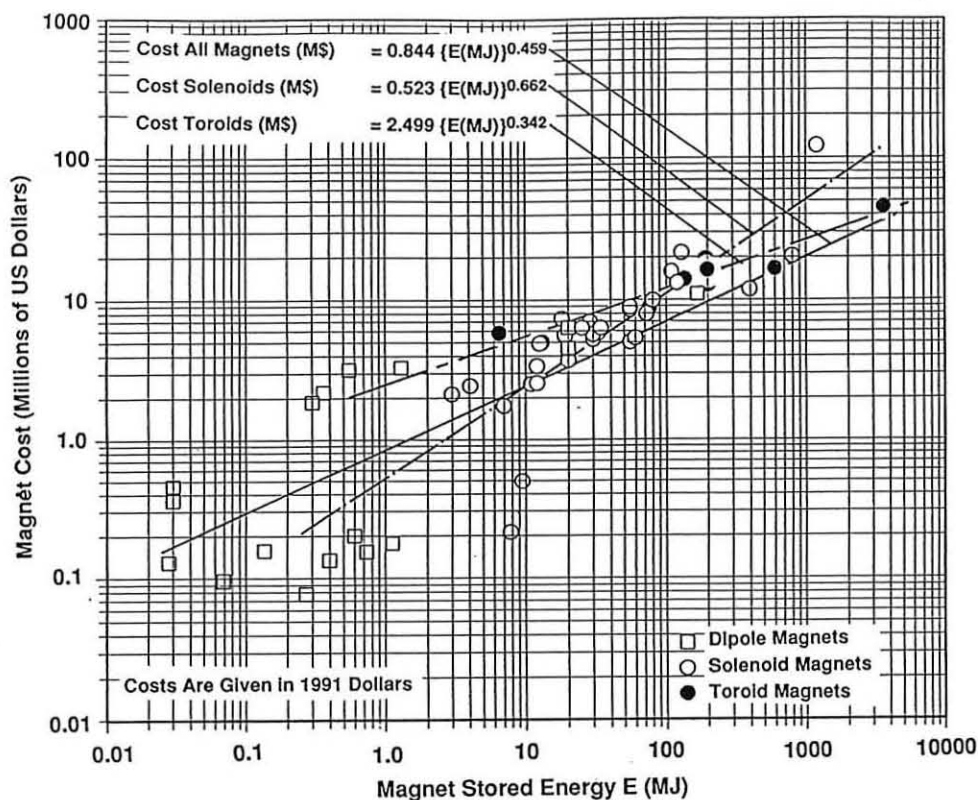


Figure 1. Superconducting Magnet Costs Versus Magnet Stored Energy.

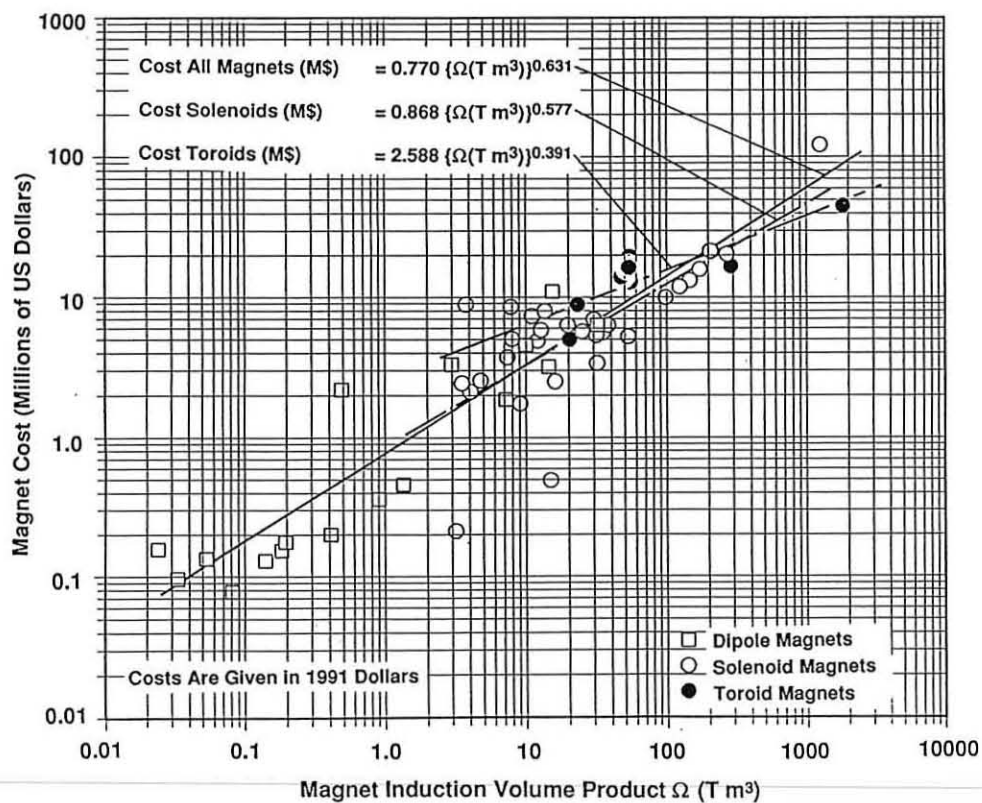


Figure 2. Superconducting Magnet Cost Versus Field-Magnetic Volume Product.

It is interesting to note that in neither case is the index even remotely close to that usually quoted in analyses of this kind.

When we separated solenoidal magnet systems, which include split coil magnets, and toroidal magnets from the data, one gets lines with different slopes (see Fig. 1 and 2). For the solenoid type of magnets, the cost equations take the following form:

$$C(\text{M\$}) = 0.523 [E(\text{MJ})]^{0.662} \quad (3)$$

and

$$C(\text{M\$}) = 0.868 [\Omega(\text{Tm}^3)]^{0.577} \quad (4)$$

where C, E, and Ω are defined as before. For the toroid type of magnets, the cost equations take the following form;

$$C(\text{M\$}) = 2.499 [E(\text{MJ})]^{0.342} \quad (5)$$

and

$$C(\text{M\$}) = 2.588 [\Omega(\text{Tm}^3)]^{0.391} \quad (6)$$

where C, E, and Ω are defined previously.

Discussion

We cannot treat accelerator and beam transport magnets in the same manner as they are invariably manufactured in considerable quantities starting from one or more prototypes. Our analysis thus provides a poor estimate of the unit cost: the prototype(s) will be wildly underestimated, while the production models will appear to be considerably more expensive. However, the total installation (accelerator, beam line) cost will follow a power law, whose constants can be determined from previously built systems.

THE COST OF HELIUM REFRIGERATION

In 1966, Strobridge, Mann and Chelton⁵ developed a technique for estimating the cost of helium refrigerators based on a limited number of cost data points available at the time. In 1969, Strobridge⁶ updated his study to include cryogenic refrigerators of all types. The cost of refrigeration was estimated based on the input power to the compressor. The 1969 Strobridge study was expanded in 1974⁷ to include a number of newer refrigerators being built at that time. During the period between 1966 and 1974, the cost of helium refrigeration did not change. From 1974 to the present, the capital cost of refrigeration appears to have escalated at the nominal rate of inflation.

This report presents one method for making a budgetary cost estimate of superconducting magnet refrigerators based on knowing what these components have cost in the past. One of the difficulties with this kind of estimate is the choice of the appropriate scaling parameter. For helium refrigeration systems, the refrigeration capacity at 4.5K is used as a scaling factor. Helium refrigeration at other temperatures is scaled to 4.5 K using the Carnot ratio. (One can divide 4.5 K by the refrigeration temperature to obtain the Carnot ratio.) Liquefaction is converted to 4.5K refrigeration by the use of the refrigeration liquefaction coefficient (typically 75 to 125 J g⁻¹).

The Thermodynamic Efficiency of Helium Refrigerators

Strobridge in his 1966⁵, 1969⁶ and 1974⁷ papers discussed the efficiency of various kinds of refrigerators. Efficiency was defined as the input power of a perfect Carnot cycle refrigerator over the real compressor power which goes into the refrigerator. An efficiency plot which contains the Strobridge helium refrigerator data as well as newer data is shown in

Figure 3. The efficiency data shown in Figure 3 shows a great deal of scatter as the original Strobridge data did. Most of the points shown in Figure 3 have liquid nitrogen precooling. The has the effect of enhancing the apparent efficiency of the machine. The addition of a liquid nitrogen precooler increases the apparent efficiency by a factor of 1.5 to 1.8.

The newer data points shown in Figure 3 show that on average the overall efficiency of helium refrigerators has not increased. There are a number of reasons for this: 1) The number of the newer points in Figure 3, (particularly those clustered between 80 and 400 W) are for machines without liquid nitrogen precooling. 2) Many of the new machines use rotary compressors (Screw compressors are the most common.). These compressors are more reliable than the older piston compressors but they are less efficient (particularly if they are small single stage machines). 3) There are more turbine expanders in smaller machines. Some of the machines built in the early 1980's are not as efficient as machines which were built later. The modern plants which are more efficient than average have two or more stages of compressors and the have expanders which are staged as well.⁸ Small piston expanders are more efficient than small turbine expanders. As the size of the plant grows, the turbine have efficiencies which are competitive with piston expanders. Large turbine are in general more reliable.

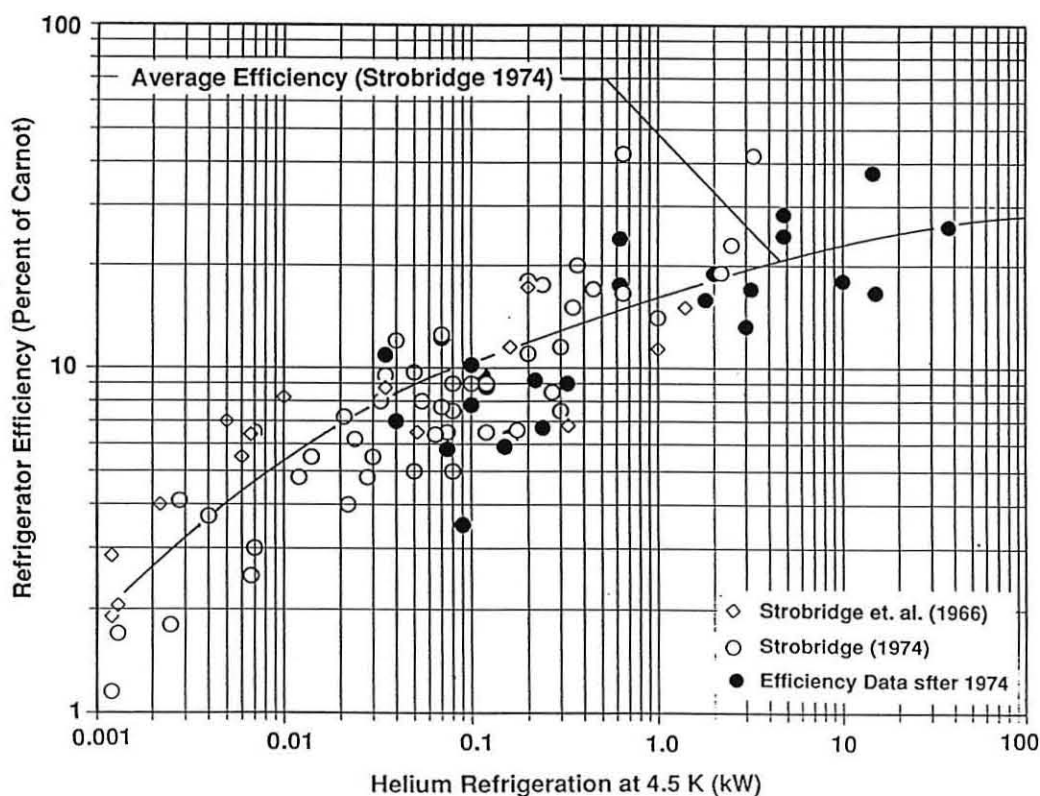


Figure 3. The Efficiency of Helium Refrigerators as a Function of 4.5 K Refrigeration

Refrigerator Cost

Figure 4 shows the cost of various 4.5K refrigerators escalated into 1991 dollars as a function of the 4.5K refrigeration. Liquefaction was converted to refrigeration using the refrigeration-liquefaction coefficient for the machine (typically 75 to 125 W per gs^{-1} depending on how the cycle has been optimized). Refrigeration at temperatures different from 4.5K has been converted to 4.5K refrigeration by using the Carnot ratio. The cost of foreign made machines was converted to dollars at the exchange rate of the year of manufacture. The dollars were escalated from the year of manufacture to 1991 dollars.

From Fig. 4, one can see that refrigerators made before 1966 are more expensive in 1991 dollars than refrigerators made after 1974. In Fig. 4 there is a line plotted with the cost points. This line represents the average cost in 1991 dollars of modern helium refrigerators which produce refrigeration from 0.040 to 15 kW. The equation for this line is:

$$C(\text{M\$}) = 1.51 [R(\text{kW})]^{0.7} \quad (7)$$

where the cost is given in 1991 dollars and R, the 4.5K refrigeration.

The small refrigerators (less than 30 W) in general cost more than the curve shown in Fig. 4. The largest plants shown in Fig. 4 are quite complex. Some have several smaller cold boxes tied together and other may include helium pump system to circulate subcooled

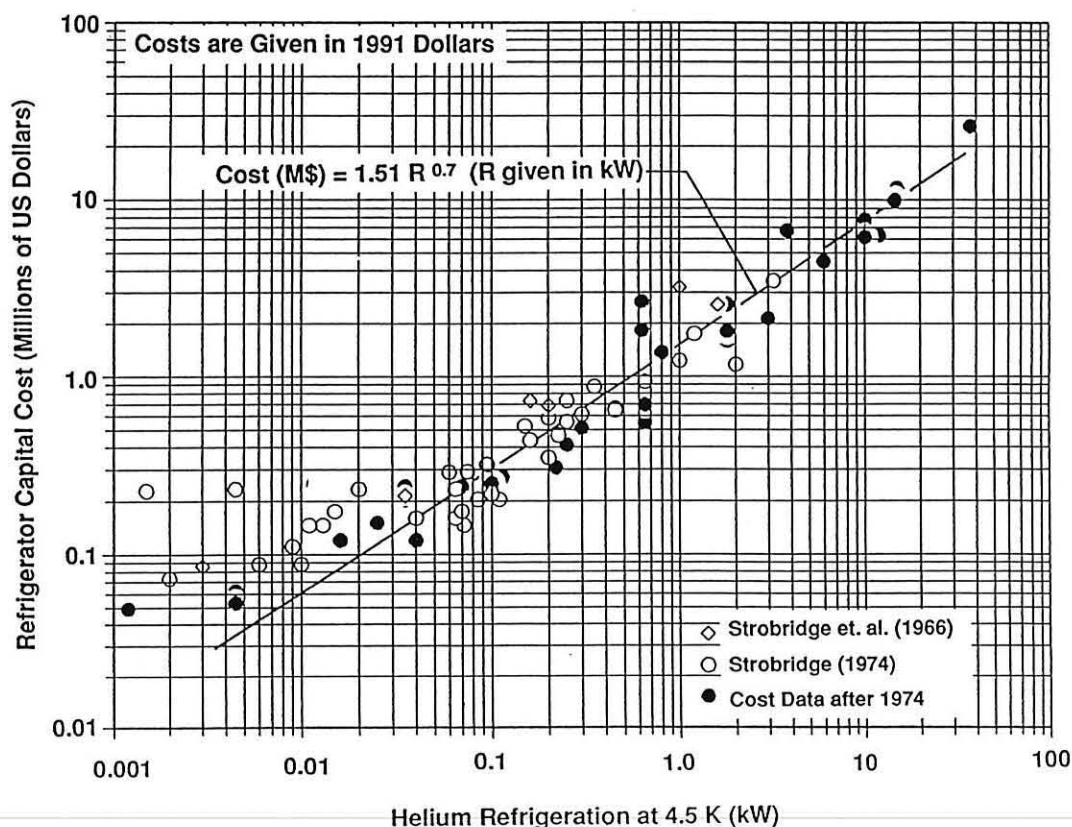


Figure 4. The Cost of Helium Refrigerators versus Refrigeration at 4.5 K

helium. As a result, these plants are more expensive. Other factors which increase the cost of refrigeration include: computer control systems (In small machines they are usually not needed.), extra purification in the cold box (sometimes a blessing, sometimes a curse), and the extra documentation required by military type specifications.

The annual cost of refrigeration can also be estimated as a function of the amount of refrigeration delivered at 4.5 K and the cost of electric power P. The annual cost of refrigeration includes; amortization of the refrigerator, depreciation, operation and maintenance labor, electric power, liquid nitrogen cooling and compressor cooling. If one assumes that 22 percent of the capital cost goes for the annual cost amortization, depreciation, operation and maintenance, the following equation can be used to estimate the annual cost of providing 4.5 K helium refrigeration for a superconducting magnet system:

$$\text{Annual Cost (M\$/yr)} = 2.72 [R(\text{kW})]^{0.78} [P(\text{\$/kWh})]^{0.56} \quad (8)$$

Equation 8 is applicable over a range of refrigeration from 0.03 to 30 kW and a range of electrical energy costs from 0.04 to 0.18 dollars per kilowatt hour. About half of the annual cost of refrigeration is related to the cost of energy and cooling. Organizations which do not amortize or depreciate their equipment can expect an annual refrigeration cost about two thirds of that given by Equation 8. The annual cost given in Equation 8 can be expected to escalate at a rate about 60 percent of the rate of inflation.

Discussion

The cost of liquid helium refrigeration can be characterized by a simple equation such as Equation 8. Multiple units change the cost picture somewhat. Unlike superconducting accelerator magnets, there are not hundred or thousands of 4.5 K helium refrigerators being made all at once. As a result, there is not much in the way of economy of scale.

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REFERENCES

1. M. S. Lubell, H. M. Long, J. N. Luton, and W. C. T. Stoddart, Applied Superconductivity Conference Proceedings, Annapolis, MD, p 341, (1972).
2. J. R. Powell, Applied Superconductivity Conference Proceedings, Annapolis, MD p 346, (1972).
3. B. M. Winer and J. Nicol, IEEE Transactions on Magnetics MAG-17, No. 1, p 336 (1981).
4. R. W. Boom, IEEE Transactions on Magnetics MAG-17, No. 1, p 340 (1981).
5. T. R. Strobridge, D. B. Mann, and D. B. Chelton, "Preliminary Analysis of Refrigeration Requirements for Superconducting Magnets in the Experimental Area of the 200 BeV Accelerator," National Bureau of Standards, Report 9259, October 1966.
6. T. R. Strobridge, IEEE Transactions on Nuclear Science, NS-16, No. 2, p. 1104 (1969).
7. T. R. Strobridge, "Cryogenic Refrigerators, An Updated Survey," NBS Technical Note 655, June 1974.
8. R. A. Byrns, "Large Helium Refrigerators and Liquefiers," Cryogenic Engineering, B. Hands, Ed., Academic Press, Inc., London (1986).